

Recent charmonium results from *BABAR*

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Recent results in the field of spectroscopy from the *BABAR* experiment are reported, with particular attention to the new states observed in ISR and $\gamma\gamma$ interactions using the full *BABAR* data sample. We confirm the states Y(4260) and Y(4360) with higher precision and for the first time the state Y(4660) is observed. We do not confirm the Y(4008) state reported by Belle. In addition, the analysis of the invariant mass of the $J/\psi\omega$ system produced in $\gamma\gamma$ interactions is presented in confirmation of the Belle observation of the X(3915) in this process.

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1 Introduction

The past 10 years represent a very highly productive period in the field of spectroscopy in physics, as many states not expected in theoretical predictions have been observed in different experiments, several decay modes and in different physics processes.

Because of their mass values and their decays to charmonium states, they are believed to have hidden charm content, and since they do not fit into the predicted charmonium spectrum they are usually referred to as *charmonium-like* states. The spin-parity assignment is in most cases unknown, therefore the standard naming convention cannot be used and they are named as X, Y or Z. They have been extensively investigated as possible candidates for non-conventional mesons, tetraquarks, glueballs or hybrids [1].

There are several ways to produce such X, Y, Z states at B factories:

- production in B decays: these are color-suppressed decays, typically processes with a B meson decaying to $X(c\bar{c})K$;
- two-photon production, for final X states with the quantum number $J \neq 1$; the process involved is $e^+e^- \rightarrow e^+e^-c\bar{c}$;
- double charmonium production: this implies positive C parity of the final charmonium $X(c\bar{c})$ state;
- production in continuum e^+e^- interactions: vector X initial states are produced in a process in which a photon is emitted from the e^+e^- initial state, followed by the production of a $c\bar{c}$ state at lower e^+e^- center-of-mass energy.

In this paper we summarize recent preliminary results from $BABAR$ in $\gamma\gamma$ interactions, and in production in e^+e^- continuum via initial state radiation (ISR) processes.

2 New results in ISR processes

2.1 Analysis of the $J/\psi\pi^+\pi^-$ system produced via ISR

The first result is related to the analysis of $e^+e^- \rightarrow \gamma_{ISR}J/\psi\pi^+\pi^-$ at $BABAR$ [2], where a clear resonant state is observed. The study of this state has been already shown from several experiments[3, 4, 5, 6]. In the previous $BABAR$ analysis a clear state at 4260 MeV/ c^2 was observed using a data sample corresponding to 211 fb $^{-1}$ integrated luminosity; now we confirm this state with higher precision using data corresponding to integrated luminosity 464 fb $^{-1}$. We do not confirm the resonant

state reported by Belle at 4008 MeV/c² in a similar analysis. The state Y(4260) is still a puzzling object; we know that its quantum numbers are $J^{PC} = 1^{--}$, because it is produced in an ISR process, but further investigation of this state is necessary. Fig. 1 shows the invariant $J/\psi\pi^+\pi^-$ mass for the full *BABAR* dataset.

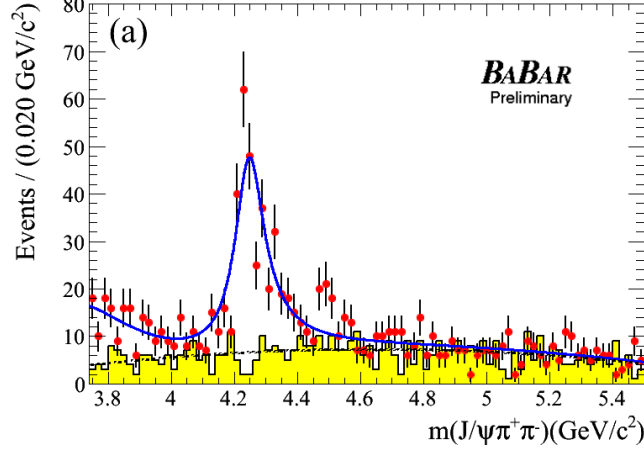


Figure 1: Invariant mass of the $J/\psi\pi^+\pi^-$ system from the process $e^+e^- \rightarrow \gamma_{ISR}J/\psi\pi^+\pi^-$.

An extended-maximum-likelihood fit is performed to the data from the J/ψ signal region and simultaneously to the background distribution from the J/ψ sidebands (yellow histogram) in the region [3.74–5.5] GeV/c². The fit function incorporates the mass-dependence of efficiency and luminosity, and uses a relativistic Breit-Wigner (BW) signal function for the Y(4260), a 3rd-order polynomial to describe the background, and an empirical exponential function to describe the excess of events below 4 GeV/c², which may result from the $\psi(2S)$ tail and a possible $J/\psi\pi^+\pi^-$ non-resonant contribution. Results for the mass and width of the Y(4260) are reported in Table 1.

The di-pion mass distribution from the Y(4260) signal region ([4.15–4.45] GeV/c²) was investigated. We define θ_π as the angle between the π^+ direction and that of the recoil J/ψ , both in the di-pion rest frame. The distribution of $\cos\theta$, which must be symmetric, is consistent with S-wave behaviour ($\chi^2/\text{NDF} = 12.3/9$, probability = 19.7%).

The $\pi^+\pi^-$ mass distribution is shown in Fig. 2, where a structure peaking around the mass of $f_0(980)$ is observed. The displacement of the peak toward lower mass suggest the possibility of interference between the $f_0(980)$ and a $\pi^+\pi^-$ continuum distribution.

A simple model is used to describe the di-pion mass distribution, namely the square of an amplitude consisting of the coherent sum of a non-resonant component, motivated by the QCD multipole expansion, and an $f_0(980)$ amplitude; the relative

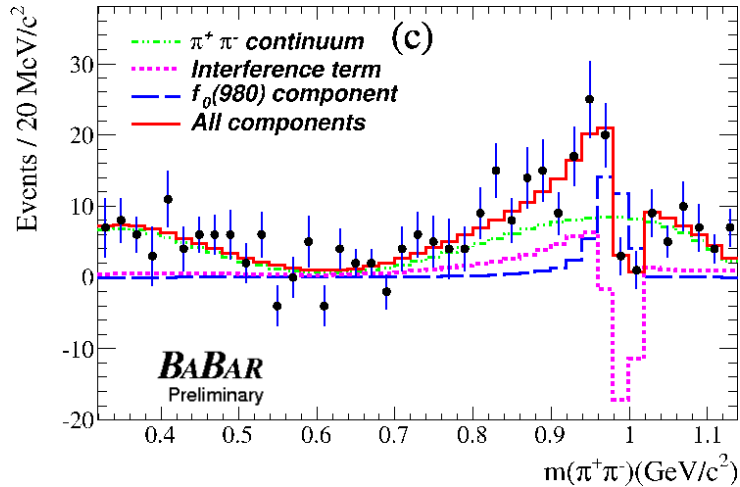


Figure 2: Fit to the $\pi^+\pi^-$ invariant mass distribution.

strength and phase of these components are free to vary in the fit to the data. The mass dependence of the $f_0(980)$ amplitude and phase is from the *BABAR* analysis of Ref.[7].

The result of the fit is shown in Fig. 2, and it is found that the $Y(4260)$ decay to $J/\psi f_0(980)$ is not a dominant contribution to the $J/\psi\pi^+\pi^-$ final state (BR $\sim 17\%$).

2.2 Analysis of the $\psi(2S)\pi^+\pi^-$ system produced via ISR

The first evidence for a resonant state at $4360\text{ MeV}/c^2$ produced in $e^+e^- \rightarrow \gamma_{ISR}\psi(2S)\pi^+\pi^-$ came from *BABAR* [8]; this was then confirmed by Belle[9]. We present an update of the *BABAR* discovery, and the confirmation of the $Y(4660)$, which was not observed in the previous *BABAR* analysis because of the limited statistics. For this new analysis in *BABAR* we made use of the full datasets collected at the $\Upsilon(nS)$, $n=2,3,4$. As these two new states, the $Y(4360)$ and $Y(4660)$, are seen in an ISR process, we conclude that their quantum numbers are the same as those of the virtual photon: $J^{PC} = 1^{--}$.

The $\psi(2S)\pi^+\pi^-$ invariant mass spectrum, corresponding to an integrated luminosity of 530 fb^{-1} , is shown in Fig. 3.

An unbinned extended-maximum-likelihood fit is performed to the $\psi(2S)\pi^+\pi^-$ invariant mass distribution for the events in the $\psi(2S)$ signal region, and simultaneously to the background distribution corresponding to the $\psi(2S)$ sideband regions (Fig. 3). In Table 1 the mass and width values obtained for the two resonances are reported.

The $\pi^+\pi^-$ invariant mass spectrum was examined for each of the two resonance regions (Fig. 4). Unfortunately we cannot arrive at any clear conclusions due to the

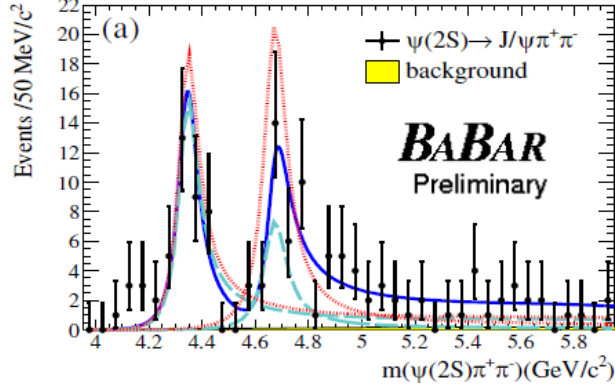


Figure 3: Invariant mass of the $\psi(2S) \pi^+\pi^-$ system from the process $e^+e^- \rightarrow \gamma_{ISR}\psi(2S) \pi^+\pi^-$.

low statistics available. However, the events tend to cluster around the $f_0(980)$ region of $\pi^+\pi^-$ invariant mass for the $Y(4660)$ signal region (Fig. 4(b)).

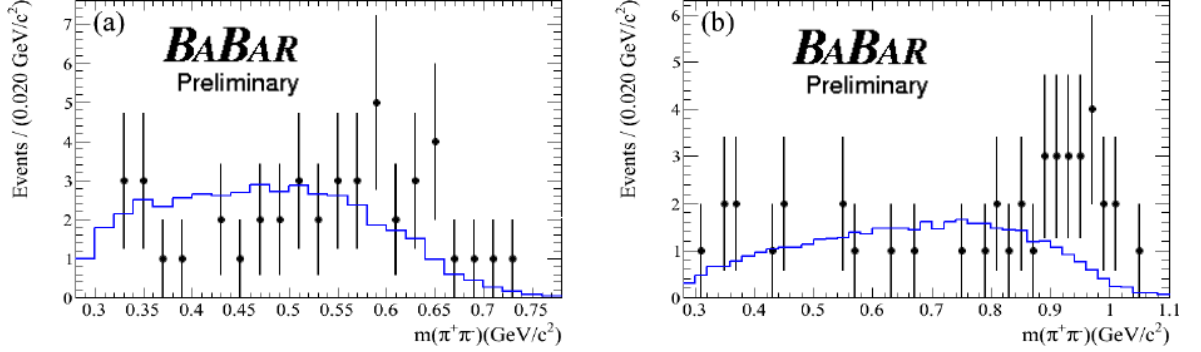


Figure 4: Dipion invariant mass distribution for the signal region of the (a) $Y(4360)$ and (b) $Y(4660)$.

Table 1: Mass and width values for the states observed in the ISR processes (*BABAR* preliminary).

Resonance	Mass (MeV/c ²)	Γ (MeV)
$Y(4260)$	$4224 \pm 5 \pm 4$	$114^{+16}_{-15} \pm 7$
$Y(4360)$	$4340 \pm 16 \pm 9$	$94 \pm 32 \pm 13$
$Y(4660)$	$4669 \pm 21 \pm 3$	$104 \pm 48 \pm 10$

3 New results in $\gamma\gamma$ interactions

3.1 Analysis $\gamma\gamma \rightarrow \eta_c \pi^+ \pi^-$

The process under study is the production of an unknown state X , where $\gamma\gamma \rightarrow X \rightarrow \eta_c \pi^+ \pi^-$. In this case X is considered to be one of the following candidates: $\chi_{c2}(1P)$, $\eta_c(2S)$, $X(3872)$ or $\chi_{c2}(2P)$, and the η_c decay process is $\eta_c(1S) \rightarrow K_S^0 K^\pm \pi^\mp$, with $K_S^0 \rightarrow \pi^+ \pi^-$. The idea is to look for the X states in $\gamma\gamma$ interactions because their observation would add useful information on their decay modes and also on the quantum numbers of the $X(3872)$. A theoretical prediction is that $\text{BF}(\eta_c(2S) \rightarrow \eta_c(1S) \pi^+ \pi^-) = 2.2\%$ [10].

Our results are reported in Table 2. No significant signal is observed, but upper limits are established on the existence of the X candidate states in a $\gamma\gamma$ process. We find that $\text{BF}(\eta_c(2S) \rightarrow \eta_c(1S) \pi^+ \pi^-) < 7.4\%$ at 90% confidence level (c.l.), which is consistent with the theoretical prediction.

Table 2: UL (90% c.l.) values obtained from the analysis of $\gamma\gamma \rightarrow X \rightarrow \eta_c \pi^+ \pi^-$ (*BABAR* preliminary).

Resonance	M_X (MeV/c ²)	Γ_X (MeV)	$\Gamma_{\gamma\gamma} \mathcal{B}$ (eV)	UL
$\chi_{c2}(1P)$	3556.20 ± 0.09	1.97 ± 0.11		15.7
$\eta_c(2S)$	3638.5 ± 5.6	13.4 ± 5.6		133
$X(3872)$	3871.57 ± 0.25	3.0 ± 2.1		11.1
$X(3915)$	3915.0 ± 3.6	17.0 ± 10.4		16
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6		19

3.2 Analysis $\gamma\gamma \rightarrow J/\psi \omega$

An interesting recent result from *BABAR* [11] involves the study of the the invariant mass of the $J/\psi \omega$ system produced via $\gamma\gamma$ interactions. After the discovery of the $Y(3940)$ state by Belle[12] in the decay $B^\pm \rightarrow J/\psi \omega K^\pm$, *BABAR* confirmed the existence of a similar resonant state in B decays[13], but with lower mass and smaller width compared to the Belle results.

In a re-analysis[14] of the *BABAR* data which used the complete $\Upsilon(4S)$ data sample and reduced the lower limit on the ω signal region to 740 MeV/c², the precision of the $Y(3940)$ measurements was improved, and evidence for the decay $X(3872) \rightarrow J/\psi \omega$ was reported. This confirmed an earlier unpublished Belle claim for the existence of this decay mode[15]. The latter was based on the behaviour of the invariant $\pi^+ \pi^- \pi^0$

mass distribution near the X(3872) mass, whereas the *BABAR* result is obtained directly from a fit to the $J/\psi\omega$ mass distribution.

A subsequent paper from Belle [16] reports the observation in $\gamma\gamma \rightarrow J/\psi\omega$ of a state, the X(3915), with mass and width values similar to those obtained for the Y(3940) in the *BABAR* analysis[13].

The preliminary result of the *BABAR* $\gamma\gamma$ analysis is reported in Fig. 5, where a resonant state around 3915 MeV/c² is observed, but no evidence for the X(3872) is found, as in the Belle paper. The peak at 3915 MeV/c² is observed with 7.6 σ significance, using the data samples collected from *BABAR* at $\Upsilon(nS)$, n=2,3,4, in total 520 fb⁻¹. A summary of the fit results is presented in Table 3. A study of the spin-parity assignment of the X(3915) is presently in progress.

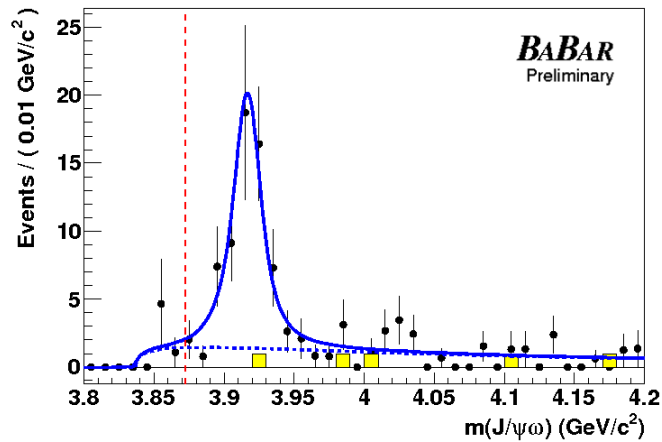


Figure 5: Invariant mass of the $J/\psi\omega$ system from the process $\gamma\gamma \rightarrow J/\psi\omega$.

Table 3: Fit values obtained for the X(3915) (*BABAR* preliminary).

X(3915)	<i>BABAR</i>	Belle
M_X (MeV/c ²)	$3919.4 \pm 2.2 \pm 1.6$	$3915 \pm 3 \pm 2$
Γ_X (MeV)	$13 \pm 6 \pm 3$	$17 \pm 10 \pm 3$
$\Gamma_{\gamma\gamma}\mathcal{B}$ (eV) , J=0	$52 \pm 10 \pm 3$	$61 \pm 17 \pm 8$
$\Gamma_{\gamma\gamma}\mathcal{B}$ (eV) , J=2	$10.5 \pm 1.9 \pm 0.6$	$18 \pm 5 \pm 2$

4 Conclusion

We have shown preliminary results from new *BABAR* analyses, in particular from ISR processes and $\gamma\gamma$ interactions. We confirm the states Y(4260), Y(4360) and Y(4660) in ISR processes, and also the existence of the X(3915) in the reaction $\gamma\gamma \rightarrow J/\psi\omega$. The state Y(4008) reported by Belle in $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ is not confirmed.

No evidence of the X(3872) was found in $\gamma\gamma \rightarrow J/\psi\omega$. It should not be present if it has $J=1$, but its absence could be due also to weak coupling to the two-photon initial state.

Many other analyses are in progress at present, and *BABAR* is still producing very interesting results 4 years after the end of data-taking.

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